Development and hydrocarbon potential of the Central Carpathian Paleogen Basin, West Carpathians, Slovak Republic

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ABSTRACT

The Central Carpathian Paleogene Basin (CCPB) lies within the West Carpathian Mountain chain and comprises the proximal facies of the West Carpathian Flysch Belt. This basin developed in a piggy-back position. It occupied the proximal zone of the accretionary wedge above the southwestward subducting oceanic slab, attached to the European Platform. The eastern part of the basin was affected by NE-SW compression, while its western portion was deformed by sinistral transpression. The tectonic events preceding and accompanying deformation of this basin must be related to convergent movements of the African, Apulian, and European plates.

The morphology of the basin floor was controlled by pre-Senonian nappe emplacement in the Inner Carpathians and Senonian thrusting in the Pieniny Klippen Belt. The depositional system was affected by shortening, uplift and shifting of the basin axis, which finally resulted in the termination of sedimentation during Oligocene-Egerian time. During the Paleogene-Karpatian period, the Pieniny Klippen Belt was detached from its substratum and shortened together with the CCPB, the external parts of the accretionary wedge, the Flysch Belt, and the internal parts of the Foreland Molasse Basin. Maximum shortening occurred in the Pieniny Klippen Belt and the proximal parts of the Flysch Belt. During the Badenian, shortening was replaced progressively by NE-SW extension, which spread from the hinterland and accommodated frontal shortening. As subduction ceased in the western Carpathian arc during Late Badenian, Early Sarmatian and Middle Sarmatian times, extension vectors gradually changed to ESE-WNW orientation in response to subduction roll-back in the Eastern Carpathians.

The CCPB has good quality seals, fair to poor quality reservoir units, and excellent to fair source rocks. Traps for hydrocarbons were formed before or contemporaneous with hydrocarbon maturation and expulsion. Maturation modeling in the basin is constrained by Middle Oligocene-Egerian and Eggenburgian-Karpatian thrusting, followed by uplift and erosion.

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INTRODUCTION

The Central Carpathian Paleogene Basin (CCPB) lies in the area of the West-Carpathian Mountain front (Fig. 1). The basin is bounded to the north by the Pieniny Klippen Belt and to the south by the Inner Carpathians (Fig. 2). This proximal region of Paleogene flysch deposition underwent significant shortening and uplift. These kinematics and erosion caused a vertical loss from 1 km in some areas to more than 2 km in other zones (Nemcok et al., 1977; Francu and Muller, 1983; Korab et al., 1986). Thus, the sedimentary record of the CCPB lacks the record of the terminal basin-fill succession. The present Paleogene outcrops are preserved in several structural subbasins which area separated by morphological or structural features, upheld by older rocks.

During the past decade, the structural remnants of the original CCPB were the focus of numerous studies. The Zilina, Liptov, Poprad and Hornad depressions (Fig. 3) and other localities studied for their hydrothermal potential were analyzed in detail by Salaga et al. (1976), Franko et al. (1984), Hanzel and Nemcok (1984) and Fusan et al. (1987). The hydrocarbon potential of the Sambron-Lipany region (Figs. 3 and 4) was explored and tested (Janku et al., 1987; Lesko et al., 1982, 1983; Rudinec, 1984, 1987, 1989; Rudinec and Lesko, 1984). Indications of gas and oil were encountered in the Lipany prospect (Fig. 4) by the wells Lipany Li-1 (gas), Lipany Li-2 (oil, gas), Lipany Li-3 (gas), Lipany Li-4 (oil, gas), Lipany Li-5 (oil, gas), Sambron PU-1(oil, gas), Saris S-1 (gas), Plavnica Pl-1 (oil, gas), Plavnica Pl-2 (oil) (Rudinec et al., 1988, 1989; Nemcok et al., 1977; Korab et al., 1986). Most of regions have insufficient geochemical data coverage for detailed

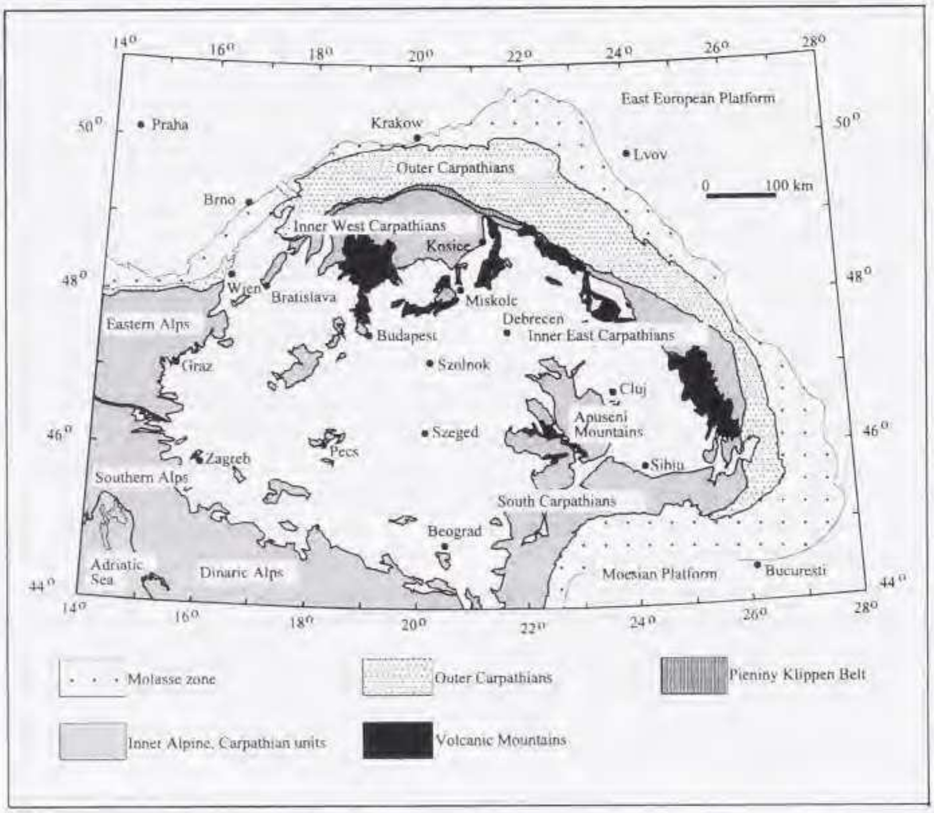

FIG. 1. Regional map of the Carpathian Arc showing major tectonic units (modified after Royden and Baldi, 1988; Sandulescu, 1988).

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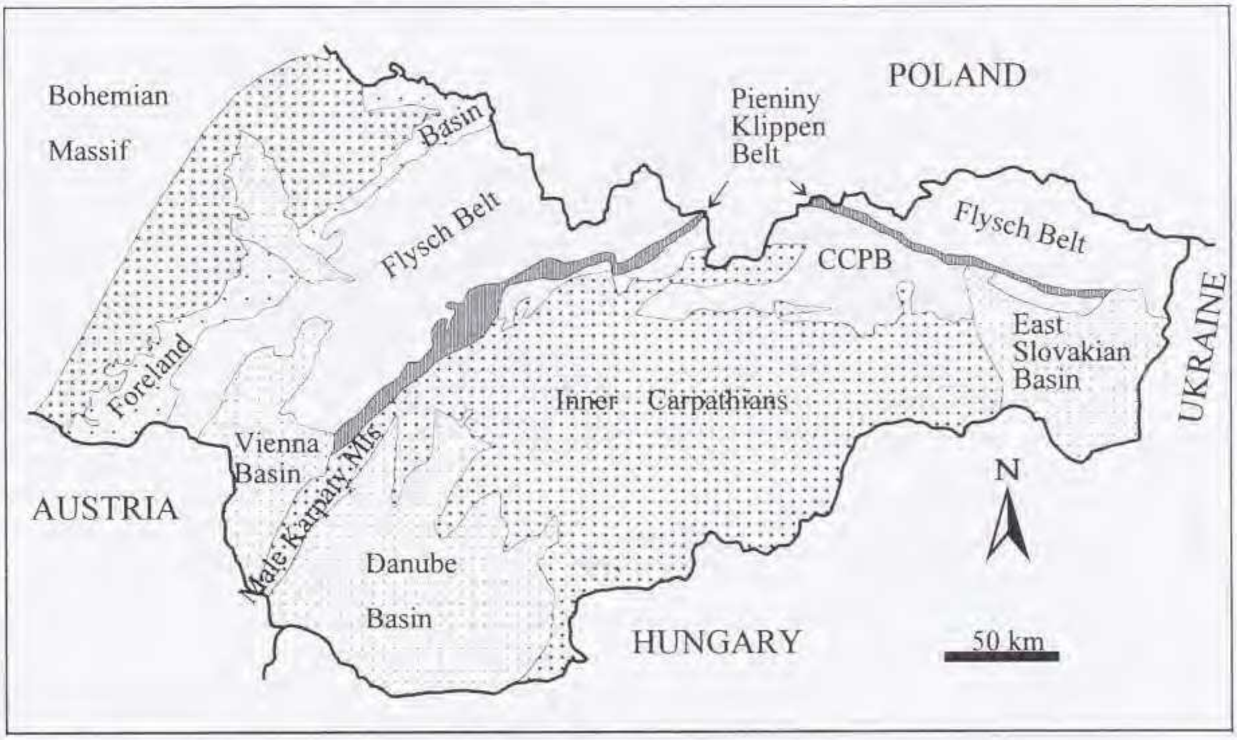

FIG. 2. Regional map of Slovakia showing the tectonic units and sedimentary basins (after Keith et al., 1991).

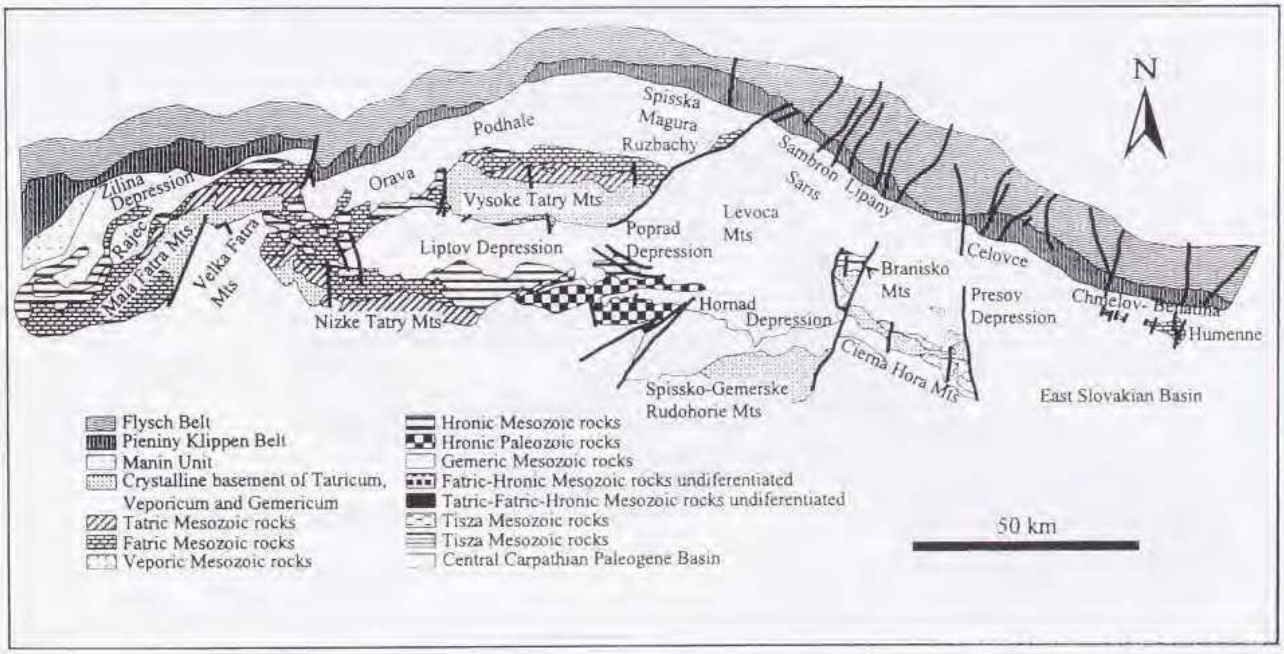

FIG. 3. Regional geological map of pre-Cenozoic surface units surrounding the Central Carpathian Paleogene Basin (after Keith et al., 1991).

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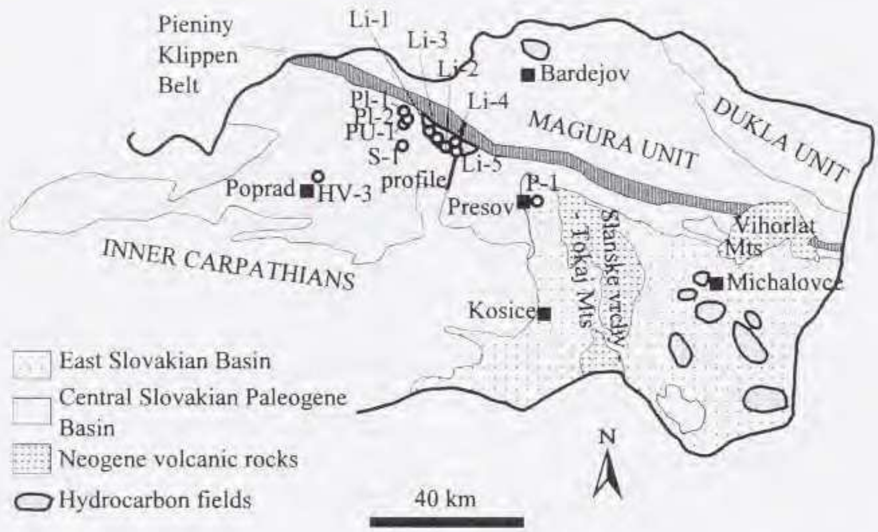

FIG. 4. Occurrences of hydrocarbon deposits, most important boreholes in eastern Slovakia (modified from Rudinec, 1989).

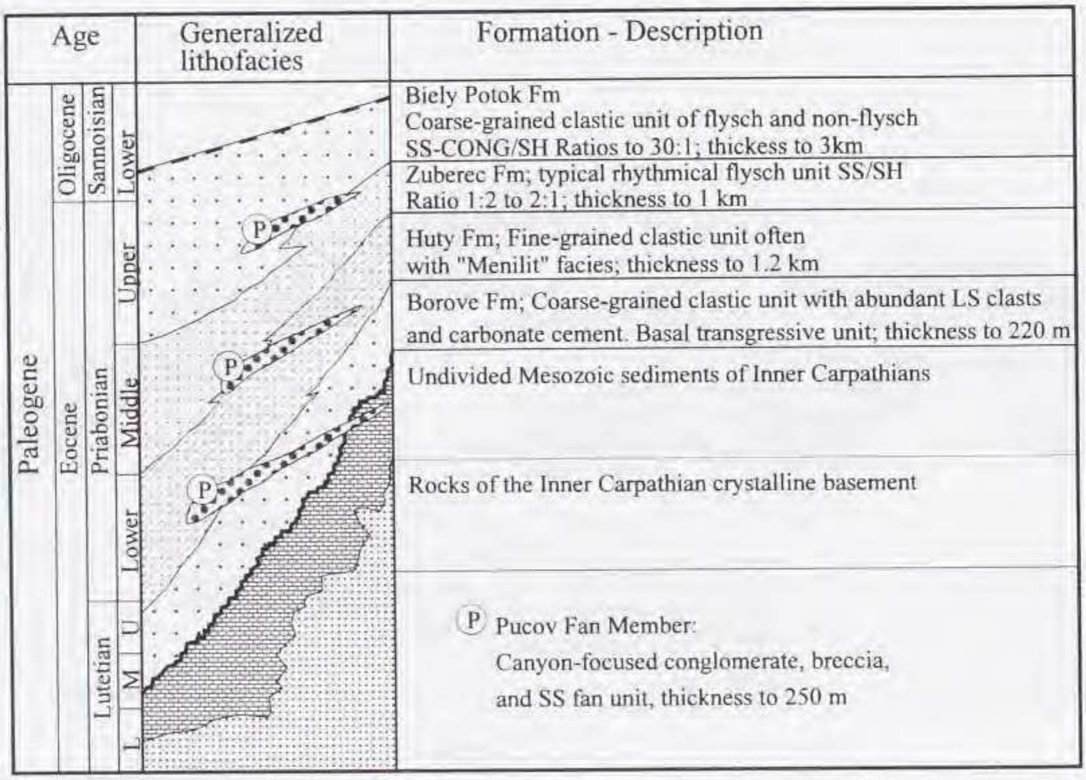

FIG. 5. Schematic lithostratigraphic column for the Central Carpathian Paleogene Basin fill (after Gross et al., 1984).

Source : MNHN, Paris

hydrocarbon evaluation. The Levoca Mountains have no reflection seismic coverage.

Each of the cited structural basins was studied separately and attempts to integrate analyses of the CCPB are rare (Marschalko, 1978, 1981, 1982; Marschalko and Misik, 1976; Marschalko and Korab, 1975; Rakus et al., 1990). The goal of this paper is to determine the model of this frontier basin and to characterize its hydrocarbon habitat by applying play concept elements which have been documented in local publications and reports. Maturation modeling was carried out by means of BasinMod™ software.

Basin models were based on available lithostratigraphical, sedimentological and structural data collected by previous workers and the authors. Structural data include measurements of faults, slickenside striations, folds, extensional veins, determination of fault displacement (e.g. Hancock, 1985; Petit, 1987; Means, 1987), measurement and determination of various fold parameters (Ramsay, 1967; Ramsay and Huber, 1983), observation of faults, vein mineralization, and cross-cutting relationships of all visible structures. Structural orientations were plotted on stereonets to analyze orientation patterns.

Fault-slip data (several thousand measurements) from more than 200 localities in and adjacent to the CCPB were used to determine palaeostress configurations. Inversion stress analysis was used to calculate principal stress orientations, magnitude ratios, and fault-slip polyphase relationships for the different events (Carey and Brunier, 1974; Angelier and Mechler, 1977; Angelier, 1990; Hardcastle and Hills, 1991). Vein and fold data, indicating the approximate orientation of principal stresses, provided a check for the afore mentioned computations.

Polyphase structural overprints were observed at most localities. A superposition of such structures permitted to observe and plot the relative movement (stress configuration) chronology at each outcrop. Timing of tectonic events was determined on the basis of the age of the deformed sediments and other geological constraints.

GEOLOGICAL DEVELOPMENT OF THE CENTRAL CARPATHIAN PALEOGENE BASIN

Data

The sedimentary fill of the CCPB is represented by the Podtatranska Group (Gross et al., 1984), summarized in the lithostratigraphic column given in Fig. 5. This sedimentary succession can be subdivided into four formations and one member.

The lowest unit of this succession is the **middle Eocene Borove Formation**, representing a basal transgressive facies, which consists of locally

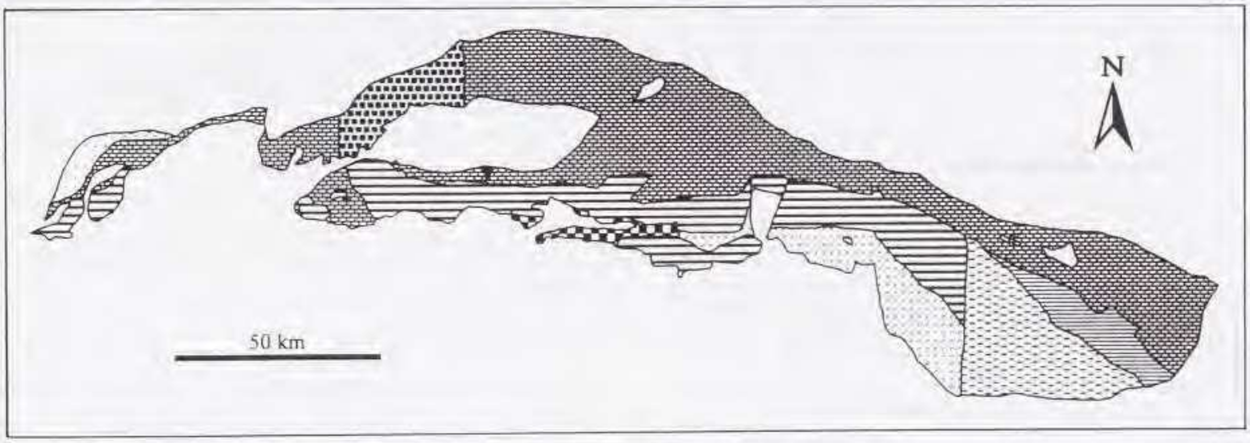

FIG. 6 Schematic geological map of pre-Cenozoic units sub-cropping in the basin floor (after Keith et al., 1991). Explanations in Fig. 3.

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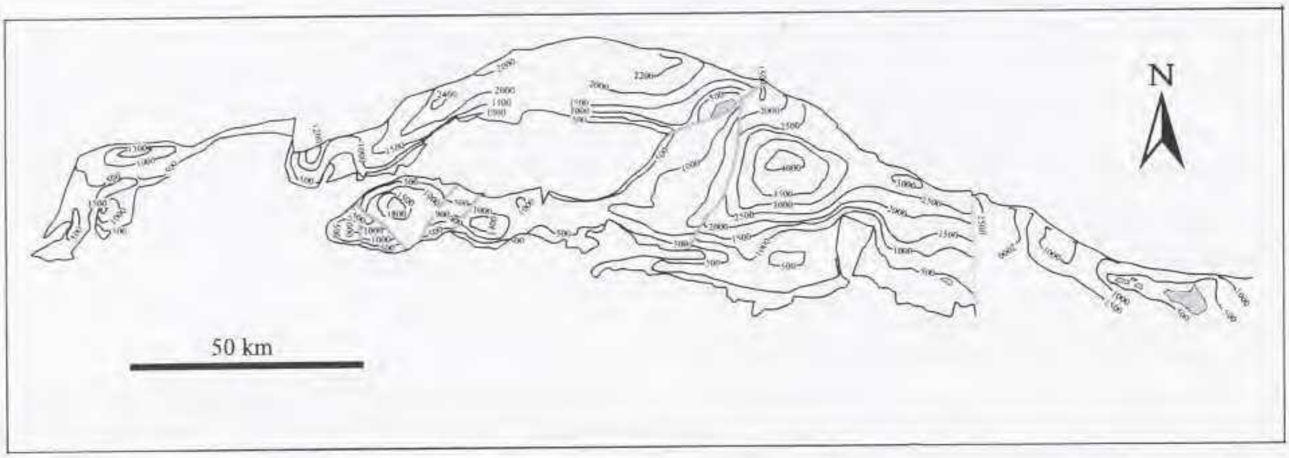

FIG. 7a. Schematic thickness map of Central Carpathian Paleogene Basin fill (after Keith et al., 1991).

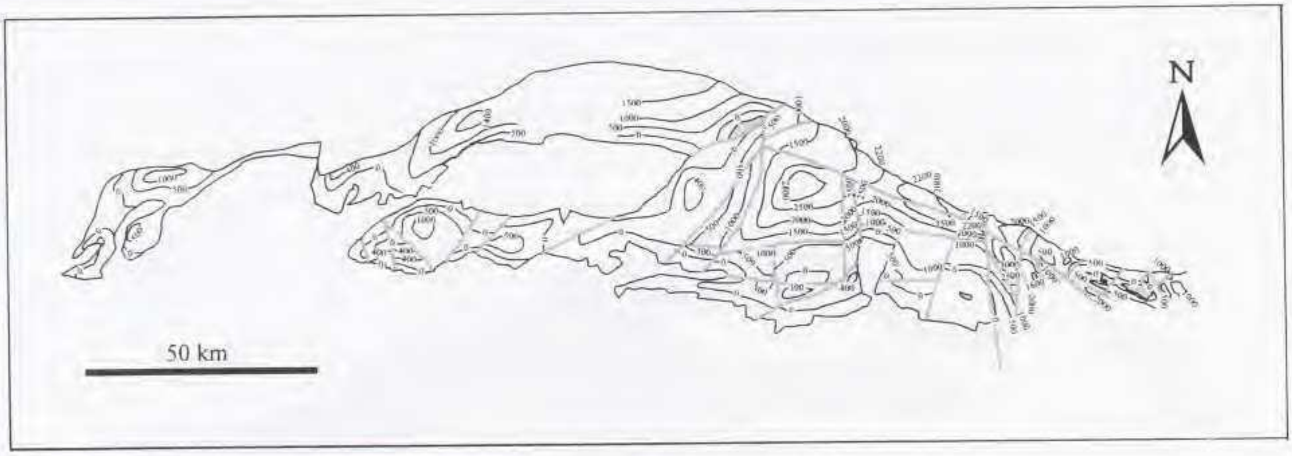

FIG. 7b. Schematic contour map of Central Carpathian Paleogene Basin floor (modified after Fusan et al., 1987). Numbers (in metres) indicate depth below the sea level.

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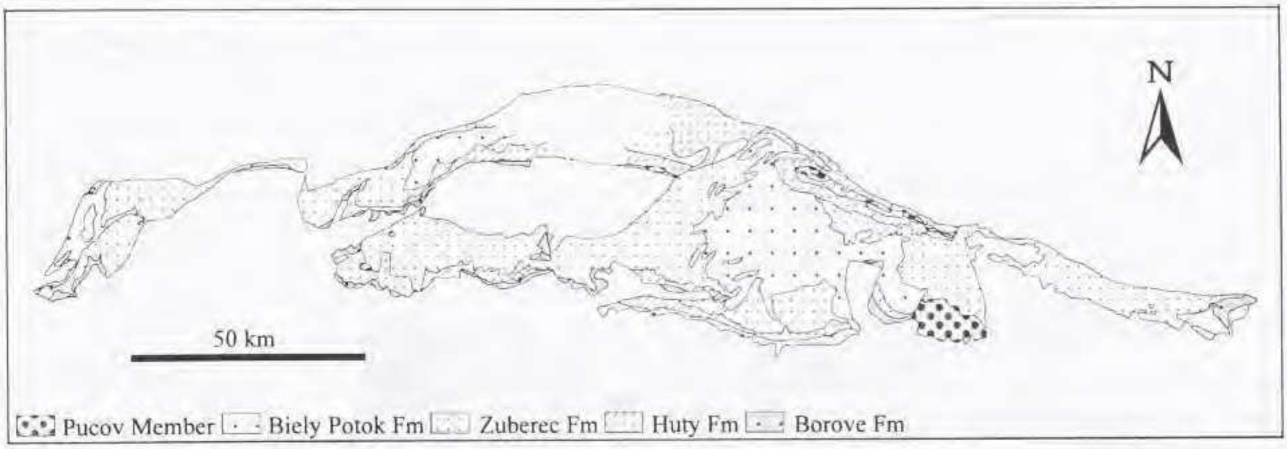

FIG. 8. Lithofacies map of Central Carpathian Paleogene Basin fill (after Keith et al., 1991).

derived breccia, conglomerate, polymict sandstone, siltstone, marl and limestone. It unconformably overlaps the pre-Senonian nappe structures of the Inner Carpathians (Andrusov et al., 1973; Biely, 1989) which consist predominantly of Mesozoic carbonates (Fusan et al., 1987) (Figs. 3 and 6).

The Borove Formation is conformably overlaid by the **middle-upper Eocene Huty Formation** which consists primarily of claystone and siltstone, containing thin interbeds of fine- to medium-grained sandstone. This unit reflects the progressive deepening of the basin. The "Menilit" facies, containing dark shale, which is best developed in the Flysch Belt, is the richest source rock and represent a member of the Huty Formation.

The u**pper Eocene Zuberec Formation** conformably overlays the fine-grained Huty deposits, indicating a change to a sandier, rhythmical flysch. The uppermost part of the basin-fill sequence is represented by the **upper Eocene-lower Oligocene Biely Potok Formation** which is a thick succession of siliciclastic flysch.

Within this succession, elongate coarse-clastic and/or brecciated carbonate turbidite fans (locally referred to as Pucov Member) can be observed at several levels. The upper portion of the regressive facies of the basin-fill sequence is missing in most of the sub-basins. The thickness of the various units is highly variable and is constrained by the morphology of the pre-Middle Eocene structures and the subsequent subsidence pattern of the basin (Figs. 7a, 7b and 8). The geometry of the basin is asymmetrical, with the deepest parts located along the Pieniny Klippen Belt (Fig. 9).

Sedimentation commenced in the CCPB contemporaneously with the development of the Carpathian arc. During the Eocene to middle Miocene period, the western part of the Carpathian orogenic belt advanced northeastwards above the southwestward subducting oceanic slab which was attached to the European Platform (Nemcok, 1993). Stress inversion studies (e.g. Nemcok, 1993) indicate that the western part of the Carpathian arc developed by sinistral transpression, while its frontal part underwent NE-SW compression. Whereas the western part of the CCPB was situated in a zone of sinistral transpression, its eastern part was located in a compressional zone (Fig. 10). The Paleogene to early Miocene stress fields computed by Nemcok and Nemcok (1994) show that a transition from NE-SW compression to N-S transpression is evident in the basin fill (Fig. 11). In this zone, as illustrated in Fig. 11, northeastward thrusting was accommodated by four large tear faults (strike-slip fault zones) which separate blocks with different uplift/erosion histories. Thrust structures related to northeastward shortening developed within a 10-15 km-wide zone along the northern margin of the basin (south of the Pieniny Klippen Belt). Shortening of up to 70 percent has been calculated for this zone. The amount of material transport by thrusting decreases southwestwards and is accommodated by folding. In the remaining parts of the basin, only strike-slip faults, N-S striking dextral and NE-SW striking sinistral

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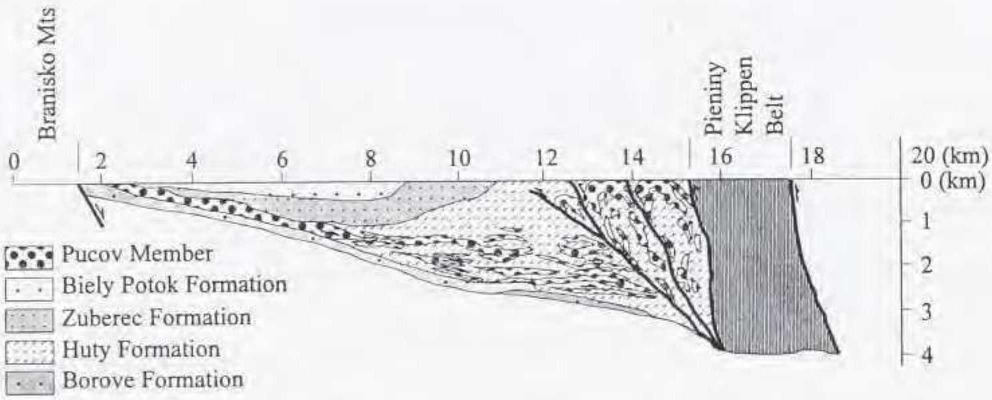

FIG. 9. Geological cross section through Central Carpathian Paleogene Basin to the North of the Branisko Mts. For location see Fig. 4.

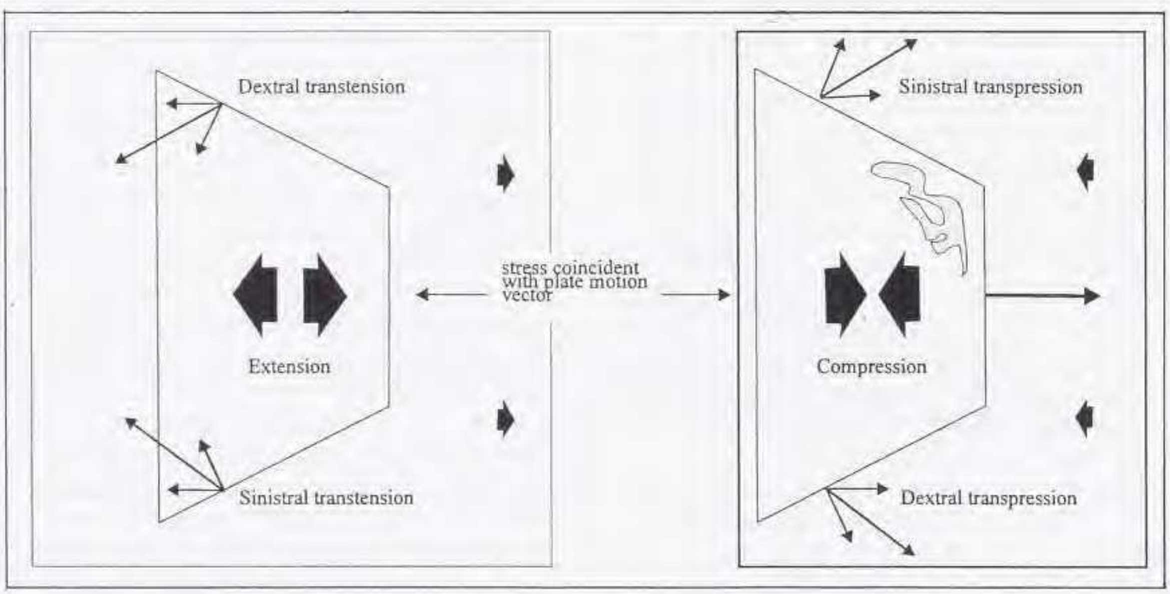

FIG. 10. Block scheme of the Inner Carpathians with Eocene - Early Miocene stress trajectories with the position and present day shape of the Central Carpathian Paleogene Basin indicated (modified after Doglioni, 1992).

Source : MNHN, Paris

faults, can be observed. Uplift, related to sinistral transpression, is indicated by apatite fission-track data (Kral, 1977, 1982; Burchart and Kral, 1982).

The youngest preserved sediments of the basin fill are early Oligocene in age. There is no evidence for continuous sedimentation during late Oligocene and Miocene times. Eggenburgian-Karpathian sediments are present in the Celovce area (Figs. 3 and 11), forming a small piggy-back basin carried by contemporaneously shortened Central Carpathian Paleogene slices. The sediments record each thrust event by the occurrence of coarse-grained sediments in the sequence. Further subsequent shortening is evidenced by Eggenburgian-Karpatian bedding becoming more highly inclined, often approaching vertical. Badenian sediments and younger rocks present in the area do not show any evidence of thrusting. Their deformational features comprise only strike-slip and normal faulting. Structural studies (Nemcok et al., 1993) indicate that the normal faulting related to NE-SW extension spread in time progressively northeastward from the Carpathian hinterland. A similar scenario is indicated by hinterland volcanism of Egerian to Sarmatian age, which becomes progressively less contaminated by crustal material with time (Poka, 1988; Salters et al., 1988; J. Lexa, 1994, personal communication).

Sarmatian arc-related calc-alkaline volcanic rocks can be found as far to the northeast as the Pieniny Klippen Belt and indicate, together with structural data, that extension progressively affected the area of the CCPB and the Pieniny Klippen Belt. Stress inversion studies (Nemcok et al., 1993) determined that during the middle-late Miocene the trajectory of extension sigma3 changed from NE-SW to WNW-ESE.

Interpretation

The CCPB development and subsequent overprint model is constrained by the structural evidence discussed above. During the Eocene to middle Miocene period, the ancestral West-Carpathians (present Inner West Carpathians) advanced northeastward over the subducting European Platform. A tapering, foreland accretionary wedge, comprising the Pieniny Klippen Belt, Flysch Belt, and allochthonous parts of the foreland molasse basin, formed as a result of progressive stacking of thrust sheets. Flysch depocenters were located immediately in front of the advancing ancestral Carpathians. The future Pieniny Klippen Belt area underwent significant uplift during early Eocene times, as indicated by apatite fission track data (Kral, 1983). This out-of-sequence thrust unit formed the northern boundary for the CCPB; this barrier was breached, however, during the early-middle Eocene by southwestward transgressions originating from the area of the Flysch Belt. Thus, the original CCPB formed since this time the proximal part of an extensive flysch depositional system (Rakus et al., 1990) which included regions of the future Pieniny Klippen Belt and the Flysch Belt. Differential thrusting in the Pieniny Klippen Belt out-of-sequence thrust unit is responsible for the different age of these transgressions in various parts of the CCPB in which the basal facies unit varies in age from Ypresian to Priabonian. For instance, the onset of basal facies deposition is Ypresian to Lutetian in the Zilina Depression (Gross et al., 1984; Samuel, 1985), Lutetian in the Orava and Sambron-Lipany area (Gross and Kohler, 1987) and Lutetian to Priabonian in the Liptov Depression, Levoca Mts., and Hornad Depression (Gross, 1985; Gross et al., 1980, 1982, 1984; Marschalko, 1965, 1966, 1981; Marschalko and Radomski, 1970; Durkovic et al., 1984). Some parts of the Pieniny Klippen Belt are characterized by the same Ypresian-aged depositional succession as the CCPB, as for the Pribradlovy Paleogen in the Zilina Depression (Gross et al., 1984). These deposits are interpreted as indicative of channels which linked the external parts of the frontal accretionary wedge with the CCPB and cut through the Pieniny Klippen Belt. A similar channel is known from the eastern part of the basin, to the East of Plavnica, Sambron-Lipany area, where it is filled by upper Eocene-lower Oligocene flysch sediments (Nemcok, 1989). Thus, the barrier provided by the Pieniny Klippen Belt probably consisted of an irregular chain of islands, which was significant enough to give rise to the development of divergent paleocurrent systems, controlling sedimentation in the Flysch Belt and in the CCPB.

The transgressive coastal onlap relationship between Paleogene sediments and the Mesozoic

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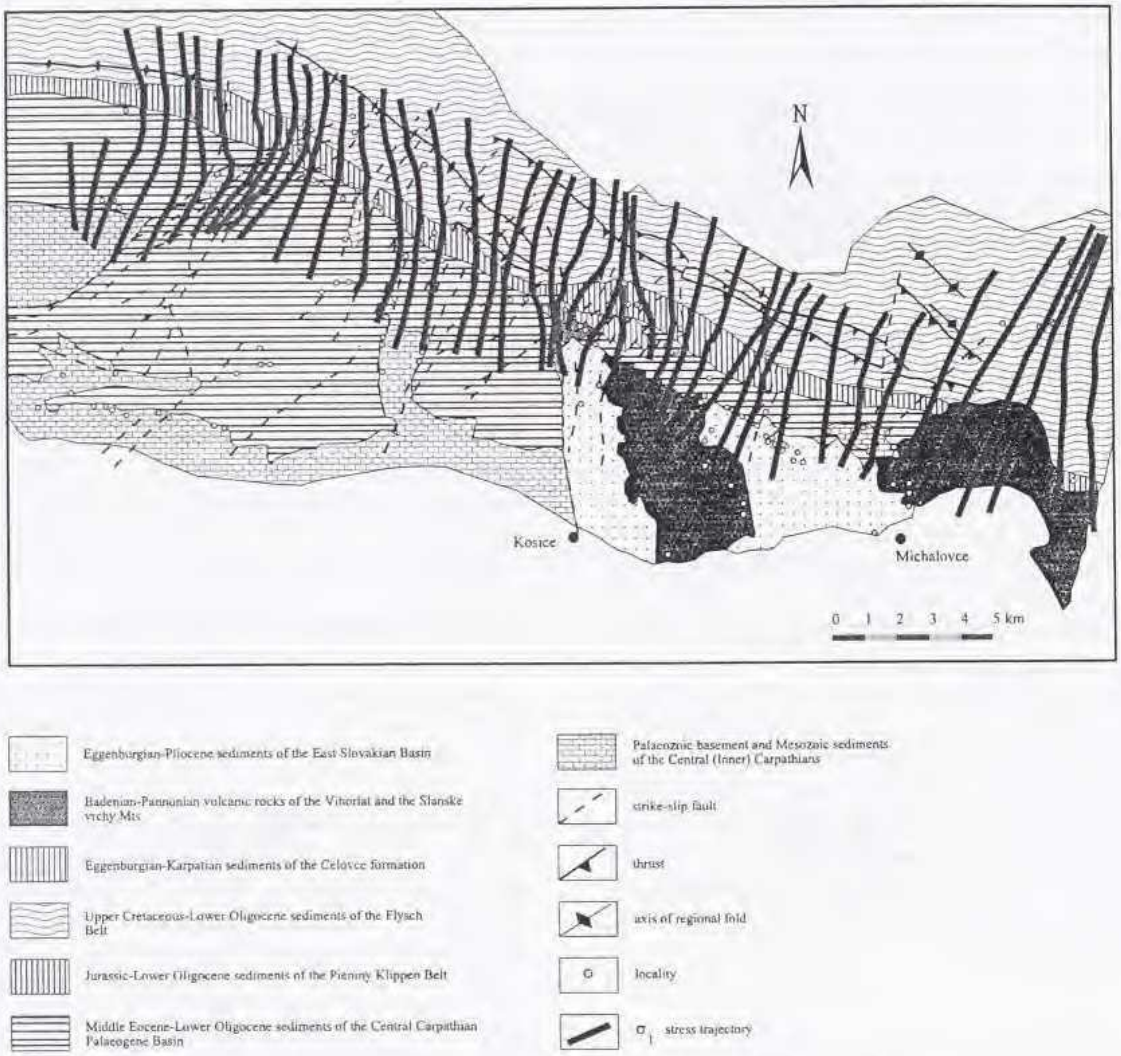

FIG. 11. Sigma1 stress trajectories in eastern parts of Central Carpathian Paleogene Basin and adjacent areas during Paleogene to early Miocene shortening (after Nemcok and Nemcok, 1994).

Source : MNHN, Paris

nappes forming the basin floor can be observed in outcrops along the southern margin of the CCPB and is also evident in wells. The basin floor was characterized by a considerable topographic relief which was upheld by various Mesozoic carbonate units. Progressive drowning of this relief gave rise to the development of buried-hill features. In the Pieniny Klippen Belt, there is only minor evidence of a corresponding transgressive coastal onlap of Paleogene sediments (Gross and Kohler, 1987), due to a strong tectonic overprint. The middle Eocene to Badenian structural position of the CCPB within the ancestral Carpathians is shown in Fig. 12. The basin floor was in most of areas generally inclined towards the Pieniny Klippen Belt (Figs. 9 and 12). However, a very dynamic evolution of the CCPB is indicated by changes in subsidence and uplift rates for different sub-basins (Rakus et al., 1990; Marschalko and Korab, 1975; Gross et al., 1980; Marschalko, 1978; Marschalko and Misik, 1976; Samuel, 1985) and by shifting of their axes (Marschalko, 1978). Additional evidence for differential uplift of a southern clastic source is indicated by the occurrence of north-vergent slump blocks at different stratigraphic level. For instance, in the Zilina and Orava Depressions, the slump structures have a late Eocene to early Oligocene age (Samuel, 1985), in the Liptov Depression, their age is middle Eocene (Gross et al., 1980) to late Eocene-early Oligocene (Gross et al., 1980, 1982), and in the eastern portion of the basin, syndepositional slump structures occur in the middle Eocene Borove Formation (Marschalko, 1965; Gross and Marschalko, 1981; Marschalko et al., 1966), in the middle Eocene-upper Eocene Huty Formation (Marschalko, 1965; Marschalko et al., 1966), in the upper Eocene Zuberec Formation (Gross, 1964, 1965; Marschalko, 1966; Marschalko and Radomski, 1970; Gross and Marschalko, 1981) and in the upper Eocene-lower Oligocene Biely Potok Formation (Gross et al., 1982; Marschalko, 1965, 1981). Clastic supply to the basin from southern sources was controlled by channels, as evident by lateral thickness and lithology changes of the flysch series.

After subsidence of the CCPB had ceased in early Miocene times, the Central Carpathian piggyback basin was overprinted by multiple tectonic phases which accompanied eastward movement of the Carpatho-Pannonian plate during the late phases of the Carpathian orogeny (Fig. 12). At the same time, while new portions of the remnant Outer Flysch Basin and molassic foreland basin were accreted to the frontal accretionary wedge, the tectonic setting of the CCPB changed from a region of the frontal accretion to a region of hinterland extension (Fig. 12). In the western portion of the CCPB, this change had a different character and progressed from frontal transpression to transtension.

The complexity in the later erosional history of different sub-basins is indicated by the fact that various structural remnants or sub-basins lack some units of the original basin-fill. The Zilina, Orava, and Liptov Depressions in the west have undergone the greatest Neogene uplift and erosion as indicated by Figures 7a and 8. In the Zilina Depression, portions of the sedimentary succession above the Zuberec Formation have been removed by erosion. This is also true for the southern part of the Orava Depression. The Biely Potok Formation is absent from the Liptov Depression. Moreover, the uppermost known portion of the Biely Potok Formation does not represent the final regressive phase of the basin-fill sequence (Gross and Marschalko, 1981; Gross et al., 1980). The thickness of the final regressive facies, although unknown, should be added to the stratigraphic units when constructing a subsidence and thermal model. Vitrinite reflectance data (Fig. 13) suggest that in the Sambron-Lipany area 1.5 to over 2 km of sediments have been removed by Neogene erosion (Francu and Muller, 1983; Korab et al., 1986).

After the middle Eocene-early Miocene period, the eastern part of the CCPB was affected by extension while frontal shortening continued (Fig. 12). At the end of the middle Miocene, the direction of the extension changed from a NE-SW to WNW-ESE orientation, driven by the subduction roll-back in the eastern parts of the Carpathian Arc (Royden et al., 1982, 1983a, 1983b; Nemcok, 1993). During the middle Miocene, the Vysoke Tatry Mountains (Fig. 3), located within the CCPB, were uplifted and subjected to erosion, as indicated by apatite fission track data (15 Ma; Cambel et al., 1990). Palaeocurrent patterns in the basin indicate that the Vysoke Tatry structure did not exist during the Paleogene.

Data from the western part of the CCPB indicate a different tectonic history. The middle

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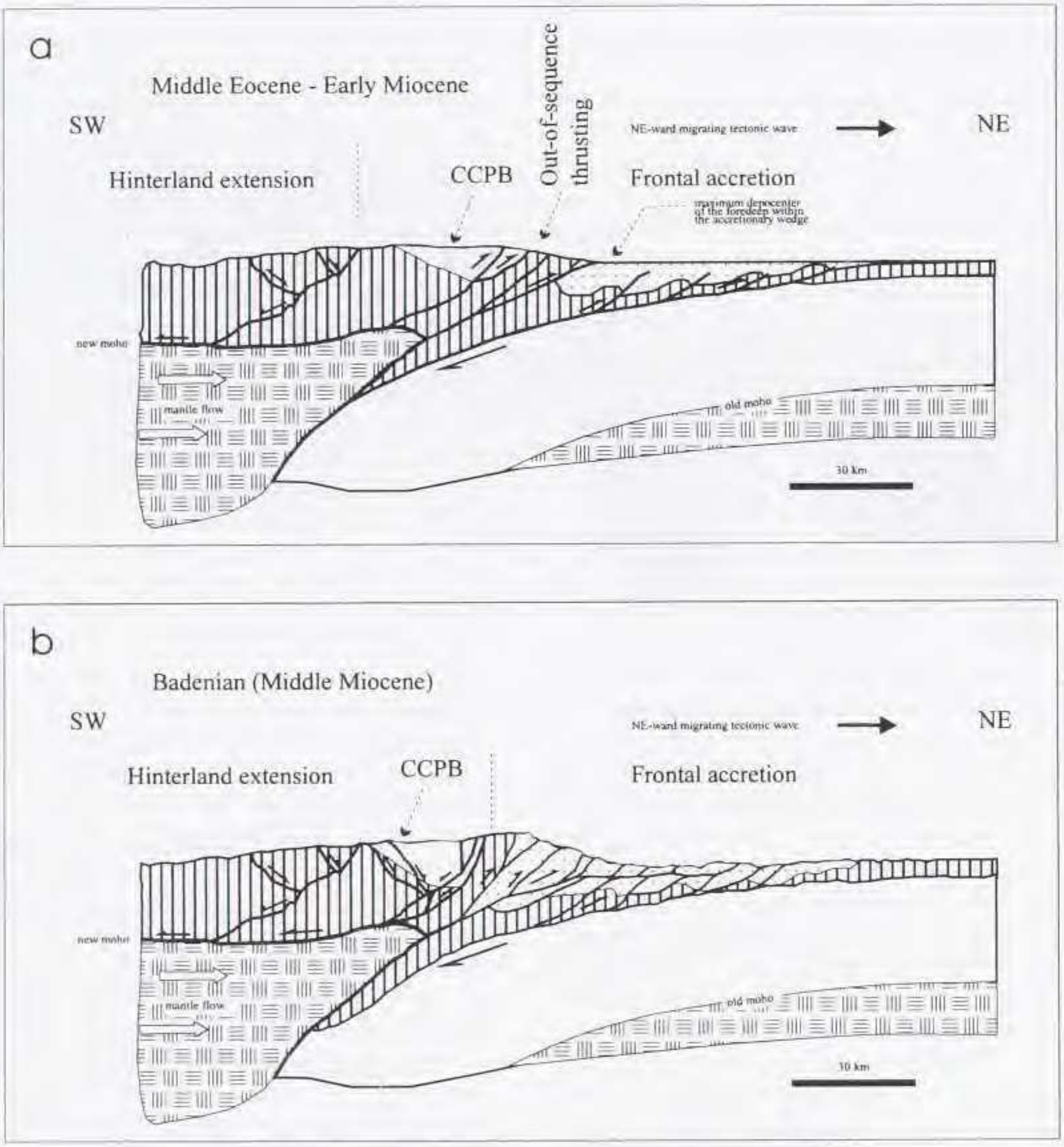

FIG. 12. Sketch profiles through eastern part of West-Carpathians showing north-eastward migration of the region of hinterland extension through time (modified after Doglioni, 1992).

Source : MNHN, Paris

Eocene to early Miocene period was characterized by sinistral transpression. Apatite fission track data from the Mala Fatra Mts. and Velka Fatra Mts. (Fig. 3) indicate that their uplift was active already during early Miocene times (Cambel and Kral, 1989).

Earthquake focal mechanisms indicate that horizontal N-S compression and W-E extension affect the area of interest (Gutdeutsch and Aric, 1976). Remeasurements of geodetic polygons indicate uplift in the western parts of the CCPB and coeval subsidence of its eastern portions (Kvitkovic and Plancar, 1979).

APPRAISAL OF THE PETROLEUM POTENTIAL OF THE CENTRAL CARPATHIAN PALEOGENE BASIN

Reservoir rocks are present within the CCPB fill and in the older, underlying sedimentary succession of the basin floor (Keith et al., 1991). Reservoirs observed within the Paleogene sequence are

(1) coarse clastic and carbonate units of the basal transgressive Borove Formation,
(2) sandstone and rare conglomerate units of the Zuberec and Biely Potok Formations, and
(3) coarse clastic turbidites of the Pucov Fans.

The quality of these reservoirs is fair to poor with an average porosity of 8 to 10% Reservoirs observed in units outside Paleogene sequence include:

(1) Eggenburgian and Karpatian sandstone and conglomerate of local extent in the Presov and Celovce areas (Fig. 3) and
(2) Mesozoic carbonate forming the basin floor which have average porosity from 1 to 14.5%. In most cases, the porosity of these carbonate reservoirs has been enhanced by fracturing. Along southern margin of the CCPB, there is evidences for their pre-transgressional karstification.

Seals within the Paleogene sequence are represented by shale of the Huty, Zuberec, and Biely Potok Formations. Other potential seals are represented by the Eggenburgian and Karpatian shale of the Presov and Celovce areas.

The quality of **source-rocks** within the CCPB sequence was determined by a limited amount of scattered data collected by various agencies in Slovakia mainly in the Sambron-Lipany area. Values of the total organic carbon content (TOC) varies between 0.1 to 1.5% for the fine-grained flysch clastics of the Zuberec Formation (14). In the Menilit shale member of the Huty Formation, TOCs of 1.1 to 10.3% were reported (Simanek et al., 1981; Hokr, 1981). Data for the Biely Potok and Borove Formations are not available. Shales of the Huty Formation, the best and thickest source-rock of the CCPB fill, has rather large areal extent within sub-basins, as indicated by Figures 8 and 9. The ratio of hydrogen and oxygen indexes of the samples from the Zuberec Formation (Fig. 15) indicates that type III kerogen (terrestrial) is prevalent with some samples indicating type II kerogen (marine-phytoplanktonic and zooplanktonic). However, it should be mentioned that interpretation of a hydrogen/oxygen index diagram in terms of type of organic matter is very hazardous, especially in the face of low TOC (matrix effect) and a high degree of maturation (Bessereau, personal com.). Various Mesozoic source-rocks have a rather low TOC (0.1-0.6%) and type II/III kerogen (Keith et al., 1991).

Potential traps can be subdivided into structural, stratigraphic, and combination structural/stratigraphic types. Structural traps are formed by:

(1) high-side thrust and anticlinal traps in a 10-15 km wide zone along the northern margin of the basin,
(2) high- and low-side normal fault traps in the remaining parts of the basin, and
(3) strike-slip fault and drag fold traps.

Source : MNHN, Paris

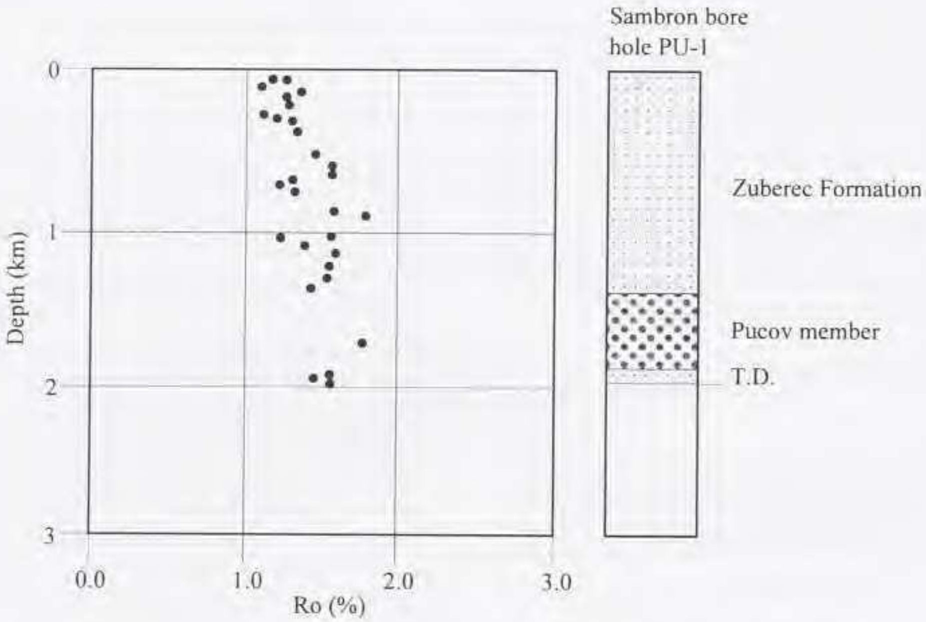

FIG. 13. Plot of vitrinite reflectance (Ro versus depth) for the Sambron PU-1 borehole (after Francu and Muller, 1983).

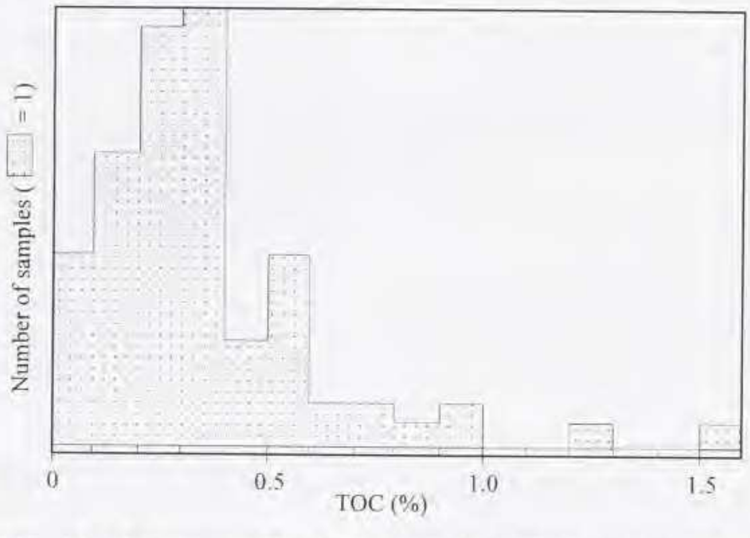

FIG. 14. Histogram of Total Organic Carbon (TOC) content of the Zuberec Formation in the Sambron-Lipany area (after Keith et al., 1991).

Source : MNHN, Paris

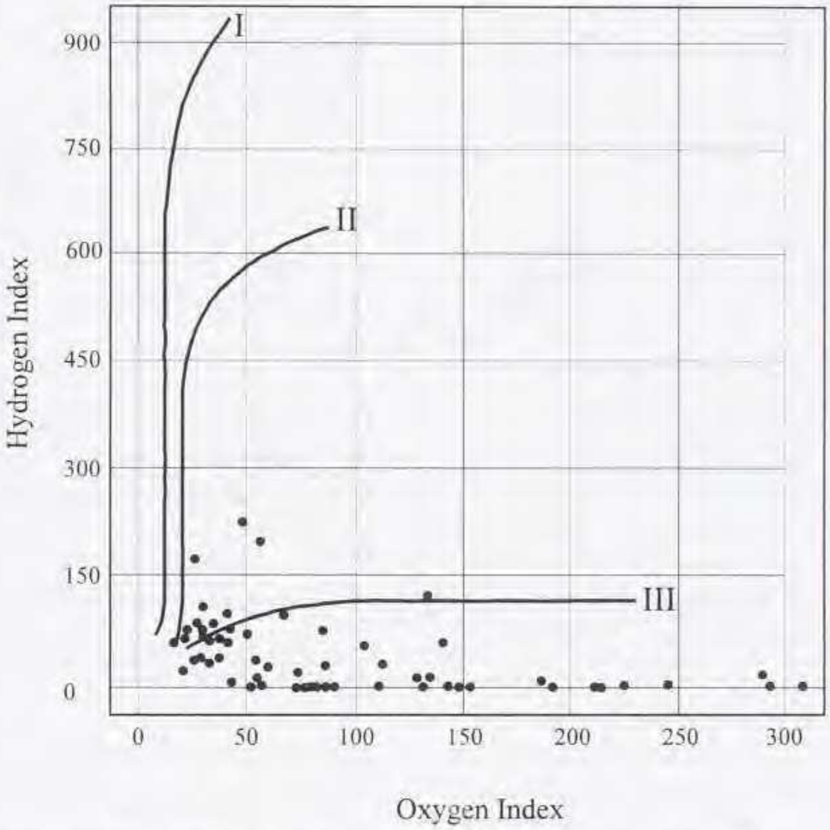

FIG. 15. Plot of Hydrogen Index versus Oxygen Index for the Zuberec formation in the Sambron-Lipany area (after Keith et al., 1991).

Stratigraphic traps are represented in the form of

(1) Pucov fans,
(2) turbiditic sandstone units,
(3) carbonate buildups on topographic highs and
(4) buried hills upheld by Mesozoic carbonates.

Combination structural/stratigraphic traps include folded Pucov fans and turbiditic sandstone units pinching-out on thrust toes.

Both horizontal and vertical migration paths can be envisaged. Lateral migration may have occurred through coarse-grained clastic units, along thrust planes, or along subhorizontal décollements. Vertical migration paths may be provided by highly permeable fractured zones, associated with strike-slip and normal fault systems.

Maturity analyses were only available from the Sambron, Lipany, Saris area (Fig. 3). As indicated by geohistory modeling, the maturity of the source-rocks in the basin sequence varies considerably due to individualized subsidence, structural and erosional histories of the different sub-basins of the CCPB. This variability is best indicated by the pyrolysis T_{max} determinations on borehole and surface samples in the structurally complex Sambron-Lipany area (Fig. 16). The location of wells discussed is shown in Fig. 4. Structures of this area comprise stacks of steeply dipping slices (Fig. 9), cut by a system of strike-slip faults (Fig. 3), accommodating inhomogeneous shortening. Burial histories of individual structures are highly variable.as indicated by T_{max} values which range from the top of the oil window (well Lipany-2), to within the oil window (surface, wells Lipany-3, 5,

Source : MNHN, Paris

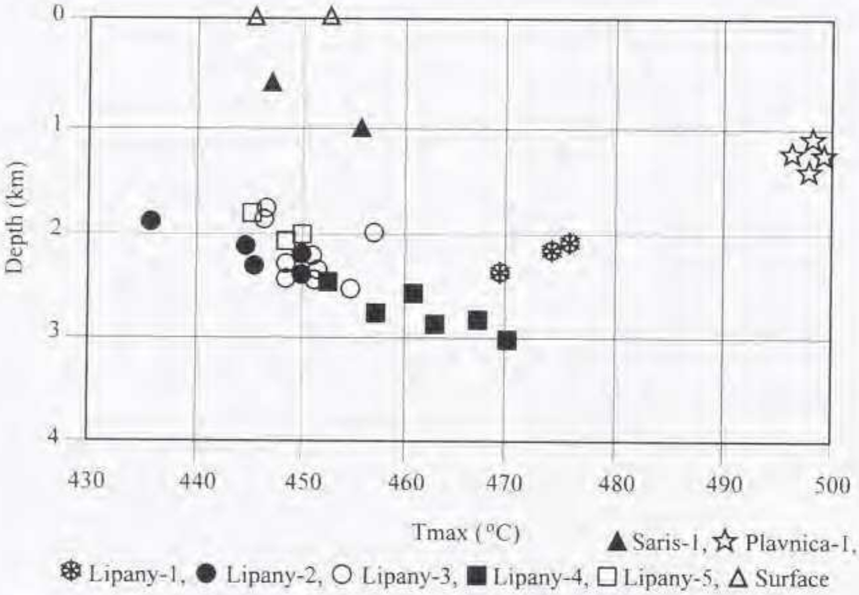

FIG. 16. Plot of Tmax versus depth for the Zuberec Formation from bore hole and surface data in the Saris-Lipany area (after Keith et al., 1991).

Saris-1), the bottom of the oil window (well Lipany-4), to the wet gas zone (well Lipany-1) or even higher maturity levels (well Plavnica-1). Analyzed samples were shales of the Huty and Zuberec Formations. Vitrinite reflectance data from the Sambron PU-1 borehole (Francu and Muller, 1983), mostly from the Zuberec Formation, indicate oil maturity to the onset of wet gas generation. Hydrocarbon generation modeling by BasinMod™ was carried out for most of areas; however, analytical data were only available for the Sambron-Lipany area. Figure 17 shows two models for the Lipany-1 well. Model A, is a simple one which assumes only sedimentary burial and erosion events (sed. mod.) and provides approximate results, whereas model B estimates sedimentary and tectonic burial and erosion (thrust mod.). Estimates of 1.5 km of missing sedimentary sequence, as indicated by vitrinite reflectance data (Francu and Muller, 1983; Korab et al., 1986), were taken into account. This is a lower limit of the suggested missing thickness range. As compared with analytical data (Fig. 16), an upper limit of missing strata of about 2-2.5 km appears to be appropriate.

Similar modeling, trying to estimate the missing parts of the sequence and taking the general asymmetry of the CCPB into account (Figs. 9 and 12), indicates that the Huty Formation and lower part of the Zuberec Formation entered the oil generation window at 30.5-27 Ma (sed. mod.) and 25-21 Ma (thrust mod.) in the Orava region, 31.5-31 Ma (sed. mod.) and 32-31 Ma (thrust mod.) in the Levoca Mts., 30 Ma (sed. model) and 23.5 Ma (thrust model) in the Sambron area, 29.5 Ma (sed. mod.; Fig. 17a) and 24.5 Ma (thrust mod.; Fig. 17b) in the Lipany area, 10 Ma (sed. mod.) and 13 Ma (thrust mod.) in the Celovce area, and 13.5 Ma (sed. mod.) and 15.5 Ma (thrust mod.) in the Presov Depression. The Huty Formation and lower part of the Zuberec Formation entered the gas generation window at about 20 Ma (sed. mod.) and 19-12 Ma (thrust mod.) in the Levoca Mts. In contrast, these source-rocks never reached the oil generation window in the Zilina, Liptov and Poprad depressions.

Fig. 17a indicates that, according to both models, the Lipany area is within the liquid hydrocarbon-generation window (sed. mod.: at depths of 2-2.8 km; thrust mod. at depths of 1.6-2.8 km). Here, the deformation occurred during middle Eocene to middle Sarmatian time (49-12.5 Ma), with the strongest shortening taking place between middle Eocene to Burdigalian times (49-17 Ma). As in other areas, hydrocarbon generation appears

Source : MNHN, Paris

to have been contemporaneous with structural trap formation. Different ages of hydrocarbon generation in Celovce area and Presov Depression are caused by lower thicknesses of the Paleogene sequence and the lower Miocene burial.

CONCLUSIONS

The evolution of the CCPB was governed by the convergence of the African, the Apulian, and the European plates during the Alpine orogenic cycle. Main phases of the basin evolution can be summarized as follows:

(1) The morphology of the CCPB floor developed during the Late Cretaceous as a consequence of the emplacement of pre-Senonian Inner Carpathian nappes and by Late Cretaceous shortening of the Pieniny Klippen Belt.

(2) During the Paleogene, the West Carpathians thrust sheets advanced progressively towards the European Platform. Differential shortening and uplift of the area of the future Pieniny Klippen Belt, together with the emergent Inner Carpathians, accompanied the subsidence of the CCPB piggyback basin. The irregular island chain of the Pieniny Klippen Belt forming its northern boundary, was an effective barrier that created divergent paleocurrent systems in the Flysch Belt and the CCPB. In the latter over 4000 m of Eo-Oligocene sediments accumulated.

(3) Subsidence and sedimentation patterns in the CCPB were controlled by active thrust tectonics resulting in shifting of the basin axis, uplift of some areas and progressive basin shortening. During Oligocene-Egerian time, this basin was deformed and uplifted to the extent that sedimentation ceased and its fill was subjected to erosion. However, continued tectonic activity was accompanied by the development of strike-slip faults which accommodated the unequal north- or northeast-vergent thrust motion of different slices.

(4) During the Paleogene-Karpatian period, the Pieniny Klippen Belt was detached from its substratum and shortened. At the same time, the CCPB, the Flysch Belts, and some of the foreland molasse units were shortened. Maximum shortening occurred in the Pieniny Klippen Belt and the proximal parts of the Flysch Belt.

(5) At the end of the early Miocene, the area of the CCPB was progressively affected by extension, which spread from the hinterland and accompanied shortening of the frontal accretionary wedge. The last significant shortening in the Zilina and Orava parts of the Carpathian arc occurred during the late Badenian. Final shortening occurred in the area north of the Vysoke Tatry during the early Sarmatian and in the area east of the Vysoke Tatry during the middle Sarmatian (Nemcok et al., 1993). Later, NE-SW extension, accommodating frontal shortening, changed orientation to WNW-ESE, driven by subduction rollback in the eastern parts of the Carpathian arc (Royden et al., 1982, 1983a, 1983b; Nemcok, 1993).

The hydrocarbon habitat of the CCPB can be summarized to include the following play concept elements:

(1) Good seals are abundant and are scattered throughout the entire fine-grained portion of the sedimentary succession.

(2) Poor to fair quality reservoir units are developed which have poorly constrained shapes and are not easily predicted, particularly within the lower portion of the sedimentary succession.

(3) Fair to excellent source-rock horizons have been identified; however, they are not distributed throughout the sedimentary column. Although oil has been discovered in the basin, it appears to be more gas prone.

Source : MNHN, Paris

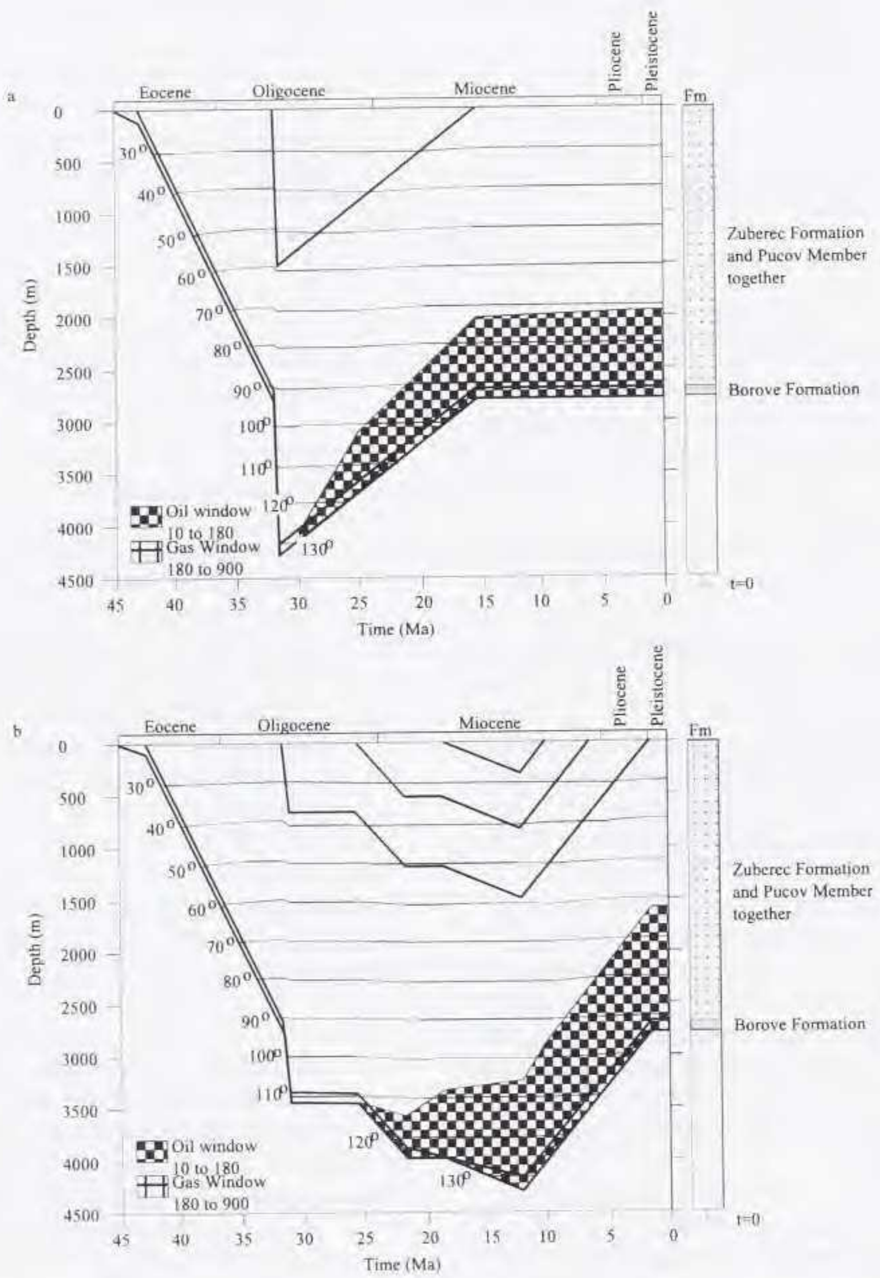

FIG. 17. BasinMod™ geohistory curve from Lipany-1 bore holedata (after Keith et al., 1991); a) sedimentary burial and erosion model, b) sedimentary and tectonic burial and erosion model.

Source : MNHN, Paris

(4) Both vertical and horizontal migration paths are provided for by faults and/or stratigraphic relationships.
(5) Traps were formed prior to or contemporaneously with the maturation of the source-rocks and the expulsion of hydrocarbons.
(6) Neogene tectonics, uplift and erosion may have caused destruction of some pre-existing accumulations.

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REFERENCES

Andrusov, D., J. Bystricky and O. Fusan (1973), Outline of the Structure of the West Carpathians. In *Guidebook for Excursion. 10th Congr. Carp.-Balk. Assoc.*, GUDS, Bratislava, pp. 5-44.

Angelier, J. (1990), "Inversion of field data in fault tectonics to obtain the regional stress-III. A new rapid direct inversion method by analytical means". *Geophys. J. Int.*, **103**, pp. 363-376.

Angelier, J. and P. Mechler (1977), "Sur une méthode graphique de récherche des contraintes principales également utilisable en tectonique et en seismologie: la méthode des diédres droits". *Bull. Soc. géol. France*, **19**, pp. 1309-1318.

Biely, A. (1989), The Geological Structure of the West Carpathians. In *Evolution of the Northern Margin of Tethys* (Edited by Rakus, M., J. Dercourt and A.E.M. Nairn). *Mém. Soc. géol. France, Paris*, N.S. **154**, II, pp. 51-57.

Burchart, J. and J. Kral (1982), "Application of the fission track isochrones method to accessory minerals of the crystalline rocks of the West Carpathians". *Geol. Carpathica*, **33**, pp. 141-146.

Cambel, B. and J. Kral (1989), "Isotopic geochronology of the western Carpathian crystalline complex: The present state". *Geol. Carpathica*, **40**, pp. 387-410.

Cambel, B., J. Kral and J. Burchart (1990), *Izotopova geochronologia krystalinika Zapadnych Karpat*. Veda, Bratislava, 183 p.

Carey, E. and B. Brunier (1974), "Analyse théorique et numérique d'un modéle mécanique élémentaire appliqué à l'étude d'une population de failles". *C. R. Hebd. Seances. Acad. Sci.*, **279**, pp. 152-164.

Doglioni, C. (1992), "Main differences between thrust belts". *Terra Nova*, **4**, pp. 152-164.

Durkovic, T., V. Gasparikova, P. Gross and J. Nemcok (1984), "Comparative study of Paleogene stratigraphy of West Carpathians". *Geol. Prace*, **80**, pp. 185-192.

Francu, J. and P. Muller (1983), "Organic matter maturity in Perri-Klippen Flysch of the Inner Carpathian Mountains (East Slovakia)". *Geol. Carpathica*, **36**, pp. 483-494.

Franko, O., P. Gross, J. Hricko and L. Zboril (1984), "Vyznam strukturnych map predterciemeho podlozia vnutrokarpatskych depresii pre vyhladavanie geotermalnych vod na priklade Liptovskej kotliny". *Puklinove a puklinovo-krasove vody a problemy ich ochrany*, GUDS, Bratislava, pp. 189-195.

Fusan, O., A. Biely, J. Ibrmajer, J. Plancar and L. Rozloznik (1987), *Basement of the Tertiary of the Inner West Carpathians*. GUDS, Bratislava, 123 p.

Gross, P. (1964), "Geologicke pomery juznej casti Levocskeho pohoria medzi Spisskym Podhradim,Pavlanmi a Levocou. Flys Zapadnych Karpat". *Zpravy o geol. vysk. v r. 1963, 2. Slovensko*, GUDS, Bratislava, pp. 118-119.

Gross, P. (1965), "Geologicke pomery juznej casti Levocskeho pohoria". *Zpravy o geol. vysk. v r. 1964, 2. Slovensko*, GUDS, Bratislava, pp. 66-67.

Gross, P. (1985), Bazalny vyvoj vnutrokarpatskeho sedimentacneho cyklu. In *Sprievodca k XXV Cel. Geol. Zjazdu Slov. Geol. Spol.* (Edited by Samuel, O. and O. Franko). GUDS, Bratislava, pp. 170-171.

Source : MNHN, Paris

Gross, P. and E. Kohler (1987), "O eocennej transgresii v oravskom useku bradloveho pasma". *Geol. Prace*, **86**, pp. 157-164.

Gross, P. and R. Marschalko (1981), "Geologia Levocskych vrchov a Hornadskej kotliny". *Zbornik IV Slov. Geol. Konferencie*. SGU, Bratislava, pp. 61-77.

Gross, P., E. Kohler, A. Biely, O. Franko, V. Hanzel, J. Hricko, G. Kupco, J. Papsova, Z. Priechodska, V. Szalaiova, P. Snopkova, M. Stranska, I. Vaskovsky and L. Zboril (1980), *Geologia Liptovskej kotliny*. GUDS, Bratislava, 242 p.

Gross, P., E. Kohler and K. Borza (1982), "Zlepencove podmorske kuzele z vnutrokarpatskeho paleogenu pri Pucove". *Geol. Prace*, **77**, pp. 75-86.

Gross, P., E. Kohler and O. Samuel (1984), "Nove litostratigraficke clenenie vnutrokarpatskeho paleogenu". *Geol. Prace*, **81**, pp. 103-117.

Gutdeutsch, R. and K. Aric (1976), "Erdbeben im Östalpinen Raum". *Arbeiten aus der Zentralanstalt für Meteorologie und Geodynamic*, **19**, pp. 1-23.

Hancock, P. (1985), "Brittle microtectonics: principles and practice". J. Struct. Geol., 7, pp. 437-457.

Hanzel, V. and J. Nemcok (1984), "Zdroj termalnej vody vo Vrbove (Popradska kotlina)". *Geol. Prace*, **81**, pp. 131-145.

Hardcastle, K.C. and L.S. Hills (1991), "BRUTE3 and SELECT: Quickbasic 4 programs for determination of stress tensor configurations and separation of heterogeneous populations of fault-slip data". *Computers and Geosciences*, **17**, pp. 23-43.

Hokr, Z. (1981), "Horlave lupky a bituminozni horniny v CSSR z loziskoveho hlediska". *Zemni Plyn a Nafta*, **26**, pp. 155-160.

Janku, J., F. Nemec, T. Korab and R. Rudinec (1987), "Vysledky vyskumnych prac na prirodne uhlovodiky na uzemi SSR a vyhladavacieho prieskumu v predneogennych utvaroch na vychodnom Slovensku v r. 1978-1986". *Knihovnicka Zemniho Plynu a Nafty*, **7**, pp. 63-75.

Keith, J.F., Jr., M. Nemcok, K.H. Fleischmann, J. Nemcok, P. Gross, R. Rudinec and W.H. Kanes (1991), *Sedimentary Basins of Slovakia, Part III, Hydrocarbon Potential of the Central Carpathian Paleogene Basin*. ESRI-University of South Carolina, Columbia, ESRI Technical Report 90-07-306, 385 p.

Korab, T. , T. Durkovic, A. Kullmanova, L. Martinsky, O. Miko, V. Gasparikova, P. Snopkova, V. Harca, J. Francu, O. Zembiak, M. Michalicek, V. Prochazkova, R. Rudinec, M. Rericha, J. Smetana, R. Jandova, E. Pichova, M. Plicka, F. Hradil, V. Filkova, D. Wunder, P. Husak and F. Karkoska (1986), *Vyskum vnutrokarpatskeho paleogenu a jeho podlozia v Sarisskej vrchovine a v Levocskom pohori. Zaverecne naftovogeologicke zhodnotenie oblasti na zaklade vrtu Saris-1. report*. Archive GUDS, Bratislava.

Kral, J. (1977), "Fission track ages of apatites from some granitoid rocks in West Carpathians". *Geol. Carpathica*, **28**, pp. 269-276.

Kral, J. (1982), "Dating of young tectonic movements and distribution of uranium in apatite of granitoid and metamorphosed crystalline rocks of the West Carpathians". *Geol. Carpathica*, **33**, pp. 663-664.

Kral, J. (1983), "Exoticky balvan v Krivej - zvysok oravskej kordillery". *Min. Slovaca*, **15**, pp. 59-65.

Kvitkovic, J. and J. Plancar (1979), Recent Vertical Movement Tendencies of the Earth's Crust in the West Carpathians. In *Geodynamic investigations in Czechoslovakia, final report* (Edited by Babuska, V. and J. Plancar). Veda, Bratislava, pp. 193-200.

Lesko, B., F. Chmelik and R. Rudinec (1982), "Perspektivne uzemie na ropu a zemny plyn vychodne od Nizkych Tatier". *Geol. Pruzk.*, **24**, pp. 37-39.

Lesko, B., T. Durkovic, O. Franko, V. Gasparikova, V. Harca, J. Nemcok, A. Kullmanova, V. Jandova, J. Kristek, M. Vanova, L. Sterba, R. Rudinec, J. Smetana, Z. Supina, D. Wunder, L. Kudera and P. Faber (1983), "Oporny vrt Lipany-1 (4000 m)". *Reg. Geol. Z. Karpat*, **18**, pp. 1-78.

Marschalko, R. (1965), "Sedimentarne textury a paleoprudenie v okrajovych flysovych litofaciach". *Geol. Prace*, **34**, pp. 75-102.

Marschalko, R. (1966), "Geology and sedimentology of marginal litofacies (Sarisska hornatina Mountains)". *Z. Karpaty*, **5**, pp. 7-102.

Marschalko, R. (1978), Vyvoj sedimentarnych bazenov a paleotektonicke rekonstrukcie Zapadnych Karpat. In *Paleogeografickyvyvoj Zapadnych Karpat* (Edited by Vozar, J., R. Marschalko, M., Misik and J. Nemcok). GUDS, Bratislava, pp. 49-80.

Marschalko, R. (1981), Podmorske naplavove kuzele v paleogene centralnych Karpat a rozsirenie flysa pod neogenom vychodneho Slovenska. In *Geologicke dni J. Slavika* (Edited by Grecula, P.). Kosice, pp. 47-64.

Marschalko, R. (1982), "Paleotektonicky vyznam flysovych sedimentov pri analyze kory alpinskej geosynklinaly". *Geol. Prace*, **77**, pp. 125-134.

Source : MNHN, Paris

Marschalko, R., P. Gross and L. Kalas (1966), "Paleogen a kvarter Hornadskej kotliny". *Geol. Prace*, **39**, pp. 95-104.

Marschalko, R. and T. Korab (1975), "Postavenie vychodoslovenskeho flysa v Karpatskom obluku. *Min. Slovaca*, **7**, pp. 53-80.

Marschalko, R. and M. Misik (1976), Metodicke poznatky zo sedimentologickeho vyskumu vychodneho Slovenska". *Min. Slovaca*, **8**, pp. 182-185.

Marschalko, R. and A. Radomski (1970), "Sedimentarne textury a vyvoj okrajovych facii eocenneho flysa pri Zdiari (Vysoke Tatry)". *Geol. Prace*, **53**, pp. 85-100.

Means, W.D. (1987), "A newly recognized type of slickenside striation". *J. Struct. Geol.*, **9**, pp. 585-590.

Nemcok, J. (1989), *Geological map of Pieniny and Cergov Mountains, Lubovnianska and Ondavska Vrchovina Uplands, 1:50 000 scale, 2 sheets*. SGU/GUDS, Bratislava.

Nemcok, J., V. Gasparikova, P. Snopkova, M. Vanova, T. Durkovic and M. Zakovic (1977), "Strukturny vrt PU-1 Sambron (Lubovnianska vrchovina)". *Reg. geol. Z. Karpat*, **8**, pp. 1-72.

Nemcok, M. (1993), "Transition from convergence to escape: field evidence from the West Carpathians". *Tectonophysics*, **217**, pp. 117-142.

Nemcok, M. and J. Nemcok (1994), "Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians". *Tectonophysics*, **233**, pp. 81-109.

Nemcok, M., J. Hok, P. Kovac, F. Marko, J. Madaras and V. Bezak (1993), Tektonika Zapadnych Karpat v Tercieri. In *Geodynamicky model a hlbinna stavba Zapadnych Karpat* (Edited by Rakus, M. and J. Vozar). GUDS, Bratislava, pp. 263-267.

Petit, J-P. (1987), "Criteria for the sense of movement on fault surfaces in brittle rocks". *J. Struct. Geol.*, **9**, pp. 597-608.

Poka, T. (1988), Neogene and Quaternary volcanism of the Carpathian-Pannonian Region: changes in chemical composition and its relationship to basin formation. In *The Pannonian Basin: A Study of Basin Evolution* (Edited by Royden, L.H. and F. Horvath). *Am. Assoc. Petrol. Geol., Mem.*, **45**, pp. 257-278.

Rakus, M., M. Misik, J. Michalik, R. Mock, T. Durkovic, T. Korab, R. Marschalko, J. Mello, M. Polak and J. Jablonsky (1990), Paleogeographic Development of the West Carpathians: Anisian to Oligocene. In *Evolution of the Northern Margin of Tethys* (Edited by Rakus, M., J. Dercourt, A.E.M. Nairn). *Mém. Soc. géol. France, Paris*, N.S. **154**, II, pp. 39-62.

Ramsay, J.G. (1967), *Folding and Fracturing of Rocks*. McGraw-Hill, New York, 568 p.

Ramsay, J.G. and Huber, M. I. (1983), *The Techniques of Modern Structural Geology. Vol. 1: Strain Analysis*. Academic Press, London, 307 p.

Royden, L.H. and T. Baldi (1988), Early Cenozoic tectonics and paleogeography of the Pannonian and surrounding regions. In *The Pannonian Basin: A Study of Basin Evolution* (Edited by Royden, L.H. and Horvath, F.). *Am. Assoc. Petrol. Geol., Mem.*, **45**, pp. 1-16.

Royden, L.H., F. Horvath and B.C. Burchfiel (1982), "Transform faulting, extension, and subduction in the Carpathian Pannonian region". *Geol. Soc. Am. Bull.*, **93**, pp. 717-725.

Royden, L.H., F. Horvath, A. Nagymarosy and L. Stegena (1983a), "Evolution of the Pannonian basin system, vol. 2: Subsidence and thermal history". *Tectonics*, **2**, pp. 91-137.

Royden, L.H., F. Horvath and J. Rumpler (1983b), "Evolution of the Pannonian basin system, vol 1: Tectonics". *Tectonics*, **2**, pp. 63-90.

Rudinec, R. (1984), "Teplotno-tlakove problemy vo flysovych oblastiach a bradlovom pasme na vychodnom Slovensku a ich vztah k ropoplynonosnosti". *Min. Slovaca*, **16**, pp. 467-483.

Rudinec, R. (1987), "Centralnokarpatsky paleogen -nova plyno-ropna provincia na vychodnom Slovensku". *Sbornik vedeckych praci Vysoke skoly banske v Ostrave*, **33**, pp. 83-98.

Rudinec, R. (1989), *Crude Oil, Natural Gas and Geothermal Energy Resources in Eastern Slovakia*. ALFA Bratislava, 162 p.

Rudinec, R. and B. Lesko (1984), "Sucasne naftovo-geologicke vysledky z flysovych suvrstvi vychodneho Slovenska". *Geol. Pruzk.*, **26**, pp. 273-275.

Rudinec, R., M. Rericha, J. Smetana and A. Stankovska (1988), *Zaverecna sprava o vyhladavacom prieskume na zivice -vnutorny flys -vyhladavaci prieskum na strukture Lipany. Vrty Lipany-2, 3, 4, 5. report*. SGU/MND Michalovce,. Archive GUDS, Bratislava.

Rudinec, R., J. Smetana and A. Stankovska (1989), *Zaverecna sprava o vyhladavacom prieskume na zivice -vnutorny flys -vyhladavaci prieskum na strukture Plavnica. Vrty Plavnica-1, 2. report*. SGU/MND Michalovce. Archive GUDS, Bratislava.

Source : MNHN, Paris

Salters, V.J.M., S.R. Hart and G. Panto (1988), Origin of Late Cenozoic volcanic rocks of the Carpathian Arc, Hungary. In *The Pannonian Basin: A Study of Basin Evolution* (Edited by Royden, L.H. and F. Horvath). *Am. Assoc. Petrol. Geol., Mem.*, **45**, pp. 279-292.

Salaga, I., K. Borza, E. Kohler, O. Samuel and P. Snopkova (1976), "Hydrogeologicke vrty v Rajeckej a Sulovskej oblasti". *Reg. geol. Z. Karpat*, **7**, pp. 1-85.

Samuel, O. (1985), Zakladne crty geologickej stavby Zilinskej kotliny. In *Sprievodca k XXV Cel. Geol. Zjazdu Slov. Geol. Spol* (Edited by Samuel, O. and O Franko). GUDS, Bratislava, pp. 87-89.

Sandulescu, M. (1988), Cenozoic tectonic history of the Carpathians. In *The Pannonian Basin: A Study of Basin Evolution* (Edited by Royden, L.H. and F. Horvath). *Am. Assoc. Petrol. Geol., Mem.*, **45**, pp. 17-26.

Simanek, V., M. Adamova and M. Strnad (1981), "Geochemicka charakteristika menilitovych vrstiev. CS Karpat". *Zemni Plyn a Nafta*, **26**, pp. 101-111.

Source : MNHN, Paris